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Research on the Calculation Method for the Wellbore Temperature of Hot Nitrogen Gas Circulation Wax Removal and Plug Removal in Offshore Oil Fields

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Abstract: The problem of wax deposition widely exists in offshore oil fields; waxing of the oil tubing will lead to a reduction in the cross-sectional area of the flow and, in serious cases, the flow path will be blocked, causing the well to stop production. In order to cope with this problem, a thermal dynamic wax removal method has emerged in recent years that utilizes hot nitrogen gas circulation between the oil tube and annulus to raise the temperature of the oil tube to achieve the purpose of wax removal and plug removal and is quick and easy to operate. Unlike conventional wellbore temperature calculation methods, the wellbore temperature field under hot nitrogen circulation conditions is influenced both by the reservoir temperature gradient and the hot nitrogen injection temperature, injection pressure, and injection rate. In this paper, a temperature calculation model for a wellbore considering both annulus injection temperature and tubing temperature and their interactions is modeled, which can consider the effects of different hot nitrogen injection temperatures, injection rates, and injection pressures. The model is used to calculate the temperature distribution for different injection parameters in order to ensure that the tubing temperature is higher than the wax precipitation temperature and that the annulus temperature is not higher than the maximum temperature resistance of the rubber in the packer. The study provides a design method for wax removal and plug removal with hot nitrogen gas circulation.

Keywords: wax deposition; wax removal; temperature calculation; hot nitrogen circulation

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1. Introduction

As crude oil contains wax in different amounts, for crude oil with a low wax content, this has little effect on production in the process of exploration; however, for crude oil with a high wax content, the original equilibrium conditions in the stratum are broken in the process of exploration with the lowering of the temperature and pressure and the precipitation of gases, and the dissolved wax will be crystallized and precipitated at a certain temperature. With the further reduction in temperature, the wax continues to precipitate, and its crystallization will increase the aggregation and deposition on the wall of the oil tube; that is, this is when the so-called wax phenomenon occurs. Generally, wax in oil wells is a brownish–black solid or semi-solid mixture of paraffin, colloid, asphalt, and oil. Sometimes, it also contains mud, sand, and water [1]. Offshore oil wells in China's Bohai Sea generally use a packer to seal the annulus between the tubing and casing. When an oil well has waxing problems, hot nitrogen of different temperatures can be injected into the annulus between the tubing and casing through the wellhead; the hot nitrogen passes through the annulus and the tubing shoes to enter the oil tubing and circulates back out of the wellhead in order to increase the overall temperature of the wellbore and achieve the effect of wax removal and plug removal.

1.1. Waxing of Oil Wells

In the production process of crude oil, the solubility of wax in crude oil and temperature, pressure, and light fraction are proportional; when the temperature and pressure reach certain conditions, the wax precipitates and adheres to the inner wall of the oil tube, as visually depicted in Figure 1. The wax deposition mechanism involves a solid layer within the tube surface. Wax deposition only occurs when the temperature of the inner surface of the tube is lower than the wax precipitation temperature. Waxing mechanisms in oil wells include molecular diffusion, Brownian motion, shear diffusion, scouring processes, etc.

Figure 1. Oil well waxing diagram.

1.1.1. Molecular Diffusion

Molecular diffusion is caused by concentration gradients. As the crude oil travels toward the wellhead, the temperature of the crude oil changes from the center of the pipe to the wall of the tube in a gradient, it becomes lower and lower, and the crude oil near the wall of the tube reaches saturation first. As the crude oil continues to flow through the tubing, molecules continue to diffuse into the sedimentary layer, leading to wax deposit layer buildup. Alnaimat et al. argue that molecular diffusion plays a dominant mechanism in the deposition of wax particles on the tube wall, whereas Brownian diffusion, shear dispersion, and gravitational settling are of lesser importance and can be neglected [2].

1.1.2. Brownian Diffusion

The small solid wax crystals suspended in crude oil are in constant collision with hotly agitated oil molecules, resulting in tiny random Brownian motion of the suspended particles. Brownian motion will result in the net transport of wax crystals to the region of reduced concentration (tube wall). In most models, researchers have neglected wax deposition due to lower tube wall temperatures due to Brownian motion. When the concentration of particles is high, the Brownian diffusion effect has a large influence due to the high probability of particle collision [3].

1.1.3. Shear Dispersion

Small suspended solid particles tend to move towards the surrounding fluid at an average velocity during laminar motion. However, the lateral movement of the particles causes a shearing effect on the fluid near the wall of the tube, which results in the migration of the wax particles towards the inner surface of the tube, and then they are finally deposited on the wall. The effect of shear dispersion on wax deposition should not be overlooked. At higher flow rates, the increase in wax particles dispersed towards the wall of the tube leads to a reduction in the effective diameter of the tube, resulting in flow obstruction. The increase in the shear rate may lead to higher pressure in the pipe, which may affect the mechanical stripping of wax deposits from the wall of the tube. Shear dispersion is the dominant process at lower temperatures, while molecular diffusion is the dominant process at higher temperatures. Goodya [4] concluded that shear dispersion plays an important role in promoting deposition when the crude oil temperature is below the cloud point and that shear dispersion has no effect on the formation of wax deposits when there is no heat flow and the deposition rate is zero.

1.1.4. Gravity Settling

The solid waxy crystals that precipitate are denser than crude oil. If these particles do not interfere with each other, they settle in the gravity field and are deposited at the bottom of the tube. Gravity settling has a negligible effect on wax deposition under seafloor flow conditions according to the experimental evidence of Burger et al. [5]. Elsharkawy et al. argued that gravity settling has not yet been recognized as an important depositional method [6].

1.2. Wax Removal and Plug Removal Method

According to the function of the process of wax removal and prevention technology, it is divided into several categories, such as the thermal process, the physical process, the electromagnetic process, the chemical process, and the biological process [7].

1.2.1. Thermal Process of Wax Removal and Plug Removal

The thermal process is an effective method of preventing and removing wax deposits because wax deposits are highly dependent on temperature. In this process, heat is provided to the production wells to prevent wax deposits, thereby increasing the flow of oil in the tube. The thermal process of wax removal and plug removal includes the hot washing process, the self-energy hot washing process, and the electric heating process [8,9].

The hot washing process is commonly used to dissolve and remove wax from tubing and wells, thereby avoiding plugging in well bores. The medium for hot washing may include hot oil, hot water, and hot nitrogen gas. The process of hot oil washing involves heating the oil to a temperature above the melting point of the wax and then pumping crude oil into the wellbore or removing the melted wax, which is effective but unsafe. The process of hot water washing has a higher heat capacity than oil at the same temperature; it can reach the deposition site at a higher temperature and is cost effective. In addition, water does not contain contaminants that may be present in oil. However, water does not provide solvency effects in hot oiling, so surfactants need to be added to improve the dispersion of the wax in the aqueous phase [10]. The process of hot nitrogen gas washing causes no corrosion to the oil tube, and no phase change will occur after injection into the well, thus avoiding the corrosion of the injected gas to the oil tube and also avoiding the shortcomings of injecting hot water or hot oil into the well to increase the amount of recovered fluids, which has been gradually applied in oil fields [11,12]. In their calculation of hot nitrogen injection unblocking temperature, Fulin Zheng et al. only calculated the temperature distribution of hot nitrogen ring air injection, in order to achieve the requirements of wax clearing and unblocking need to be higher injection temperature, poor economic efficiency [13]. Xianjun Man et al., in the use of steam hot wash cleaning wax, after verification, relying on the ring air body convection heat transfer heating tubular column, were only able to clean the wellbore 500 m below the wellhead [14].

The self-energy hot wash process is a new technology applied in oil fields. The principle is to use natural gas- or oil field-associated gas in the casing as the fuel material, with the pumping machine from the oil wells as the medium. The fluid is rapidly heated by equipment and then enters the casing space; with the pump as the driving force, the high-temperature liquid is injected back into the oil well, and the temperature of the whole annular casing space increases [15,16].

The electric heating process involves lowering a cable into the well. A large amount of electric current is passed through the walls of the tube, which converts electrical energy into heat to dissolve wax deposited on the wall of the tube and increases the temperature of the crude oil in the well to ensure the normal flow of crude oil. The problem of flow assurance due to wax precipitation can be dealt with appropriately by this method as it effectively controls the temperature above the formation region [17].

1.2.2. Physical Process of Wax Removal and Plug Removal

The physical process of wax removal and plug removal is to remove the wax deposited on the inner wall of the tube with the help of mechanical tools, and the wax scraped off will be carried to the wellhead with the flow of crude oil. The main advantage of this technology is that it can remove the wax at a fixed point; the operation is simple, and the effect is fast. The disadvantage is that it is time-consuming and laborious.

1.2.3. Electromagnetic Process of Wax Removal and Plug Removal

The electromagnetic process of wax removal and plug removal is relatively advanced technology at present. This process is based on prevention and combined with other removal and anti-dewaxing technology. Its working principle is to transform electric energy into magnetic energy through the use of a magnetic field; under the action of a high-strength magnetic field, paraffin molecular rearrangement changes the crystallinity of the wax. Under a high-strength magnetic field, wax molecules rearrange to change the crystallinity of the wax and overcome the phase aggregation of wax molecules. This reduces the viscosity of the crude oil, thus increasing the mobility of the crude oil. It also reduces the viscosity of the crude oil so that wax particles do not deposit on the surface of the tube wall. The disadvantage of this technique is the magnetization of the pump, and the direction and strength of the magnetic field in the oil field should be considered when using the magnetic wax removal process.

1.2.4. Chemical Process of Wax Removal and Plug Removal

On the one hand, the chemical process of wax removal and plug removal involves injecting chemicals into oil wells to react with wax to improve the flow properties of the crude oil and to reduce the precipitation temperature of waxes in the crude oil and their adhesion to the wall of the tube, so as to effectively prevent wax deposition. Solvents are commonly used to treat wax deposits in production formations and can also be used to remediate formation damage [18]. On the other hand, this makes use of the heat generated by the chemical reaction to heat the wells and to melt the waxes that have been deposited.

1.2.5. Microbiological Process of Wax Removal and Plug Removal

The microbiological process of wax removal and plug removal mainly uses the growth and reproduction of microorganisms to destroy the internal structure of wax molecules in crude oil, change the composition of the wax particles, and hinder the crystallization of the wax molecules to inhibit the deposition of paraffin molecules. Sood used the strain Geobacillus TERINSM to degrade paraffinic crude oils at high temperatures and low oxygen and low nutrient conditions. Their results showed that high molecular weight paraffinic crude oils were degraded while low carbon chains were unaffected [19].

1.3. Wellbore Temperature Calculation Method

In the process of oil field exploration, wellbore designing, drilling, cementing, testing, the thermal recovery of heavy oil, etc., the calculation of the wellbore temperature field is very critical. The wellbore temperature is calculated to obtain reasonable wellbore structure and injection parameters to ensure wellbore safety and production efficiency.

Ramey regarded the wellbore as an infinite long line heat source inserted into the formation; the heat is mainly transferred along the radial direction, ignoring the heat loss along the direction of the well body, and based on the conservation of energy and momentum, the total heat transfer coefficient of the system is used to optimize the calculation model by replacing multiple thermal resistances [20]. Satter adds condensation effects to the undersaturated, saturated, and superheated steam calculations, distinguishing it from the Ramey model, which treats the heat transfer coefficient as a variable rather than quantitative [21]. Willhite proposed a formula for calculating the total heat transfer coefficients of water and steam injection based on the results of existing scientific research.

For the total heat transfer coefficient of a water and steam injection formula, after the calculation of a simple example, the actual measurement confirms the rationality of the formula [22]. In order to explain the heat flow at the wellbore and ground interface density variations at the wellbore and ground interface, the semi-transient method and the principle of time superposition were used by Hasan et al. to add a constant heat source for a sustained period of time to indicate the heat flow density [23]. Yao et al. addressed the problem that high condensate is prone to wax precipitation and aggregation during the lifting process of the wellbore, thus blocking the production tube and affecting the normal production of oil wells, and established the corresponding calculation model of wellbore temperature field by applying the basic principles of heat transfer, obtained the viscosity and temperature curve of high condensate through their experiments, researched the transition of wellbore fluid flow, and discovered the way to solve the problem of wax formation in oil wells [24]. Ding et al. established a two-dimensional transient temperature field calculation model for wellbores applicable to both positive and reverse circulation well pressurization processes and used the finite difference method for the model's solution. The finite difference method was chosen for modeling. This method provides a theoretical basis for the field measures to control the change in wellbore temperature [25]. The hot nitrogen gas circulation dewaxing method adopted in this paper makes full use of the formation energy by circulating the hot nitrogen gas in the formation, and heats the inner and outer walls of the oil pipes that appear to be waxed twice. Compared with the non-circulating hot nitrogen dewaxing method, this method fully utilizes the energy of the formation and has a better heating effect on the oil pipe.

2. Crude Oil Wax Extraction Testing

Crude oil samples were collected from a block in the Bohai Sea of China, and wax precipitation experiments were carried out using the water bath observation method, in which the wax precipitation point of the crude oil was tested by controlling the temperature rise and fall of the water bath box.

2.1. Experimental Equipment

The purpose of this experiment was to observe the wax precipitation of crude oil samples at different temperatures through the water bath heating method under normal temperature and pressure conditions to determine the wax precipitation point temperature of crude oil. The water bath experimental setup (−5~90 °C), crude oil sample, funnel, beaker, pure water, and industrial alcohol were as depicted in Figure 2.

Figure 2. Experimental equipment diagram.

The indicators of this experimental apparatus and equipment are as follows:

(1) Temperature control range: −5–90 °C
(2) Temperature fluctuation: ±0.1 °C
(3) Temperature resolution: 0.1 °C

(4) Temperature rising rate: 0.1–20 °C/min
(5) Temperature cooling rate: 0.1–10 °C/min

2.2. Experimental Procedure and Experimental Results

The crude oil wax precipitation experimental process was as follows:

(1) Check that the equipment and the power supply to the experimental equipment are normal;
(2) Make a 7:3 ratio of industrial alcohol to pure water and pour it into the water bath box;
(3) Turn on the water bath experimental equipment, set the temperature of the water bath box to −5 °C, and wait for the temperature of the water bath box to drop to the set temperature;
(4) Pour 50 mL of crude oil sample into the beaker and place it smoothly in the water bath box;
(5) Leave the crude oil sample for 10 min and wait for the crude oil temperature to drop to the set temperature;
(6) Set the temperature of the water bath box, so that the water bath box begins to warm up, every 5 °C to record changes in the crude oil samples and shoot a video;
(7) Record the maximum temperature of the water bath box so that the water bath box is able to cool down, with cooling every 5 °C to record the changes in the crude oil samples, and take photos of the changes in the crude oil;
(8) Record the wax precipitation of the crude oil at different temperatures in the water bath.

The experimental results are shown in Figure 3.

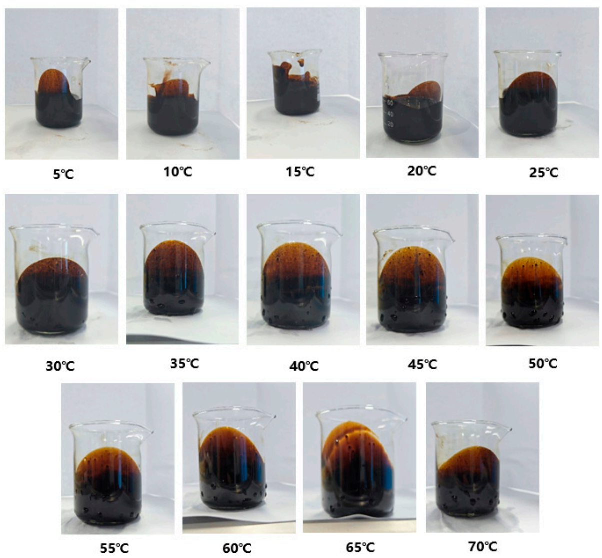


Figure 3. Experimental results diagram.

At the water bath temperature of 2–20 °C, there were more wax crystals attached to the wall of the cup, with poor fluidity, and the number of wax crystals did not change significantly during the warming process. At the water bath temperature of 25–40 °C, the number of wax crystals attached to the wall of the cup showed no obvious change, the fluidity was better, and the number of wax crystals showed no obvious change during the warming process. At the water bath temperature of 45–60 °C, the number of wax crystals at the wall of the cup decreased significantly, the fluidity was good, the number of wax crystals on the wall of the cup decreased significantly in the process of warming up, and the wax crystals melted at the highest level during the temperature range of 45~50 °C. At the water bath temperature of 65–70 °C, there were essentially no wax crystals at the cup wall, and the fluidity was good.

Through examining the performance characteristics of the crude oil samples at different temperatures, it was possible to determine that the wax crystals of the crude oil began to dissolve after reaching 45 °C.

3. Calculation Model of Wellbore Temperature Field for Hot Nitrogen Cycling

The hot nitrogen circulation method is used to increase the temperature inside the tubing by injecting hot nitrogen into the annulus and returning it from the tubing. It is necessary to calculate the temperature distribution of the casing and the temperature distribution of the tubing at the same time, and the mathematical model for calculating the temperature distribution of the wellbore under the conditions of hot nitrogen circulation will be established in this chapter.

3.1. Heat Transfer Analysis

The hot nitrogen in the annulus, on the one hand, transfers heat to the casing through heat convection, and it passes through the casing wall, the cement ring, and the formation in turn through heat conduction and dissipates outward; on the other hand, the hot nitrogen in the annulus transfers heat to the tubing through heat convection, and it passes through the tubing wall through heat conduction and dissipates inward. At the same time, the injected hot nitrogen will return from the tubing after circulating to the bottom of the well, and the hot nitrogen will also heat the tubing when it carries the heat from the formation and flows in the tubing. Therefore, the thermodynamic effects of the two flows must be combined to calculate the temperature of the wellbore. It is assumed that at the time of calculating the wellbore temperature distribution, the wellbore has been circulating hot nitrogen for injection for some time and that the temperature transfer process is steady state heat transfer. As heat transfer and raising the temperature of the tubing is a beneficial loss of heat from the high-temperature nitrogen, heat transfer in the direction of the tubing is not considered.

3.1.1. Heat Convection Model

When the fluid flows over the surface of the object, the fluid temperature and surface temperature of the object are different, and the heat exchange process is known as convective heat transfer. Heat convection is the joint role of the results of the fluid convection and thermal conductivity. The following equation can be listed as:

$$Q = hA(t_w - t) \tag{1}$$

where Q is the heat transfer per unit time; h is the convective heat transfer coefficient; t_w is the temperature of the surface; t is the temperature of the fluid; and A is the area of heat convection.

The flow in an annulus and a circular tube injected with a large amount of hot nitrogen is turbulent, and the heat transfer process occurs only in the fluid. In calculating the convective heat transfer coefficient for turbulent flow, the Dittus-Boelter formula is commonly used.

The equation for flow in tubing can be listed as:

$$N_{fu} = 0.023\mathrm{Re}_f{}^{0.8}\mathrm{Pr}_f{}^{\mathrm{n}} \tag{2}$$

The equation for flow in tubing can be listed as:

$$N_{fu} = 0.023\left(\frac{d_1}{d'}\right)^{0.53}\mathrm{Re}_f{}^{0.8}\mathrm{Pr}_f{}^{1/3} \tag{3}$$

$$h_f = \lambda \cdot Nu_f / D \tag{4}$$

where Re_f, Pr_f are the Reynolds number and the Prandtl number in the fluid, respectively, in which the Reynolds number receives the influence of the injection pressure; d_1 is the outer diameter of the annulus; d' is the inner diameter of the annulus; n = 0.4 when the fluid is heated and n = 0.3 when the fluid is cooled.

3.1.2. Heat Conduction Model

Heat conduction is the transfer of heat between different temperature bodies in an object that are in contact with each other or with different temperatures without relative displacement. The following equation can be listed as:

$$Q = k\frac{\Delta t}{L}A \tag{5}$$

where Δt is the temperature difference between the two sides of the flat wall; k is the thermal conductivity; and A is the area of the flat wall perpendicular to the direction of heat conduction.

3.2. Thermodynamic Calculation Model

During the flow of hot nitrogen in the annulus and tubing, the temperatures in the annulus and tubing influence each other. This thermodynamic model calculates the temperature in the annulus and tubing separately and then obtains the temperature equilibrium solution through iteration.

3.2.1. Tubing Heat Transfer Model

The convective heat transfer of nitrogen during the flow of the tubing can be listed as:

$$\mathrm{d}\overline{Q} = h(T - T_{oi})\mathrm{d}A = 2\pi r_{oi} h_{f1}(T - T_{oi})\mathrm{d}L = \frac{T - T_{oi}}{R_{f1}}\mathrm{d}L \tag{6}$$

where h_{f1} is the tubing convection heat transfer coefficient; T is the nitrogen temperature; T_{oi} is the temperature of the inner wall surface of the tubing; r_{oi} is the inside diameter of the tubing; and R_{f1} is the convective heat transfer resistance of the tubing.

Conduction heat transfer through the tubing can be listed as:

$$\mathrm{d}\overline{Q} = 2\pi\lambda_1 \frac{T_{oi} - T_{oo}}{\ln\left(\frac{r_{oi}}{r_{oo}}\right)}\mathrm{d}L = \frac{T_{oi} - T_{oo}}{R_1}\mathrm{d}L \tag{7}$$

where R_1 is the tubing conduction heat transfer coefficient; r_{oo} is the outside diameter of the tubing; and T_{oo} is the temperature of the outer wall of the tubing.

3.2.2. Annulus Heat Transfer Model

The convective heat transfer between nitrogen during the flow in the annulus and the inner wall of the casing can be listed as:

$$\mathrm{d}\overline{Q_1} = h_{f2}(T - T_{ti})\mathrm{d}A \tag{8}$$

The convective heat transfer between nitrogen during the flow in the annulus and the outer wall of the tubing can be listed as:

$$\mathrm{d}\overline{Q_2} = h_{f2}(T - T_{oo})\mathrm{d}A \tag{9}$$

The transformation leads to the following equation:

$$\begin{aligned} \mathrm{d}\overline{Q_1} &= \tfrac{T - T_{ti}}{R_{f2}}\mathrm{d}L, R_{f2} = \tfrac{1}{2\pi r_{ti} h_{f2}} \\ \mathrm{d}\overline{Q_2} &= \tfrac{T - T_{oo}}{R_{f3}}\mathrm{d}L, R_{f3} = \tfrac{1}{2\pi r_{oo} h_{f2}} \end{aligned} \tag{10}$$

where h_{f2} is the annular air convection heat transfer coefficient; T_{ti} is the temperature of the inner wall of the casing; r_{ti} is the inner diameter of the casing; and R_{f2}, R_{f3} is the convective heat transfer thermal resistance at the outer wall of the tubing and the inner wall of the casing.

Conduction heat transfer through the casing, cement layer, and rock layer can be listed as:

$$\begin{cases} \mathrm{d}\overline{Q_t} = 2\pi\lambda_1 \frac{T_{ti}-T_{to}}{\ln\left(\frac{r_{to}}{r_{ti}}\right)} \mathrm{d}L \\ \mathrm{d}\overline{Q_c} = 2\pi\lambda_2 \frac{T_{to}-T_c}{\ln\left(\frac{r_c}{r_{to}}\right)} \mathrm{d}L \\ \mathrm{d}\overline{Q_\tau} = 2\pi\lambda_3 \frac{T_c-t_\tau}{\ln\left(\frac{r_\tau}{r_c}\right)} \mathrm{d}L \end{cases} \tag{11}$$

By transforming Equations (10) and (11), we can obtain:

$$\mathrm{d}\overline{Q} = \frac{T-t_\tau}{R_2} dL, R_2 = \frac{1}{2\pi r_{ti} h_{f2}} + \frac{\ln\left(\frac{r_{to}}{r_{ti}}\right)}{2\pi\lambda_1} + \frac{\ln\left(\frac{r_c}{r_{to}}\right)}{2\pi\lambda_2} + \frac{\ln\left(\frac{r_\tau}{r_c}\right)}{2\pi\lambda_3} \tag{12}$$

where $d\overline{Q_t}, d\overline{Q_c}, d\overline{Q_\tau}$ is the heat that passes through casing, concrete and rock layers; λ_1, λ_2, λ_3 is the thermal conductivity of the casing, concrete, and rock layers; T_{to} is the casing outer wall temperature; T_c is the temperature of the outer wall of the concrete; t_τ is the temperature of the rock layers; and r_{ti}, r_{to}, r_c, and r_τ are the inner radius of the casing, the outer radius of the casing, the outer column surface radius of the concrete, and the outer column surface radius of the rock layers, respectively.

The total thermal resistance of the transfer between the annulus fluid temperature and the tubing fluid temperature can be listed as:

$$R_3 = R_{f1} + R_1 + R_{f3} = \frac{1}{2\pi r_{oi} h_{f1}} + \frac{\ln\left(\frac{r_{oi}}{r_{oo}}\right)}{2\pi\lambda_1} + \frac{1}{2\pi r_{oo} h_{f2}} \tag{13}$$

The ultimate effect of convective heat transfer and heat conduction is to cause the high temperature nitrogen to be exothermic, the enthalpy to decrease, and the temperature of the tubing to rise.

$$-\mathrm{d}Q = \mathrm{d}\overline{Q}$$

This can be considered to be:

$$-Q_m \mathrm{dh} = -\,Q_m C_p \mathrm{dT} = \frac{T-t_\tau}{R_2}\mathrm{d}L + \frac{T-T_o}{R_3}\mathrm{d}L \tag{14}$$

where T is the nitrogen temperature in the annulus; T_o is the nitrogen temperature in the tubing; Q_m is the mass flow rate of nitrogen; and C_p is the constant pressure heat capacity of nitrogen.

Similarly, the equation for the heat transfer of nitrogen in the tubing can be listed as:

$$-Q_m \mathrm{dh} = -\,Q_m C_p \mathrm{dT} = \frac{T-T_a}{R_3}\mathrm{d}L \tag{15}$$

where T is the nitrogen temperature in the tubing and T_a is the nitrogen temperature in the annulus.

From Equations (14) and (15), the tubing fluid temperature and the annulus fluid temperature interact with each other, and an iterative computational method is used to calculate the final tubing and annulus temperature distributions.

Firstly, only the temperature distribution of hot nitrogen injection into the annulus under the influence of formation temperature is calculated. Secondly, the temperature distribution of nitrogen outflow from the tubing under the influence of annulus temperature is calculated. Finally, the final equilibrium temperature distribution of the two temperature distributions under the influence of each other is calculated several times according to the initial temperatures of the annulus and the tubing.

3.3. Hot Nitrogen Cycle Temperature Distribution

Based on the data from the A1 well in the Bohai Sea of China, the well depth is 2493 m, the inner and outer diameter of the tubing is 62 mm and 73 mm, the outer diameter of the casing is 137 mm and 151 mm, and the hole diameter is 315.9 mm. The thermal conductivity of the wall of the tube is 45.3 W/(m·K), the thermal conductivity of the cement ring is 1.4 W/(m·K), and the thermal conductivity of the rock is 2.8 W/(m·K). The output of the well is, the nitrogen injection volume is 1200 m^3/h, and the injection temperature is 120 °C. Finally, the ground temperature is 20 °C and the ground temperature gradient is 0.03 °C/m.

3.3.1. Effect of Injection Pressure on Wellbore Temperature

The wellbore temperature at different injection pressures was calculated as shown in Figure 4. With the injection pressure rising from 15 MPa to 30 MPa, the temperature distribution in the wellbore showed a slight increase, but the overall temperature distribution in the wellbore showed little change. It can be seen that the injection pressure has little effect on the temperature of the wellbore, and only a suitable injection pressure can be ensured to inject the hot fluid into the wellbore.

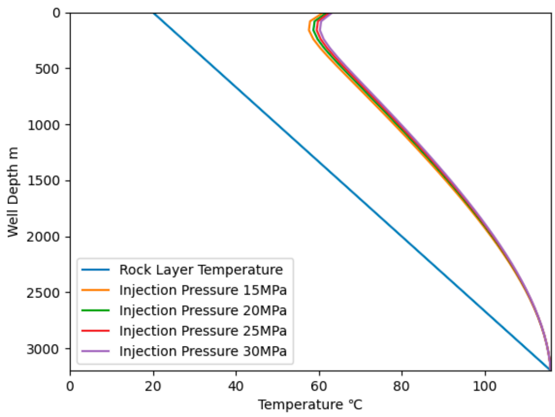


Figure 4. Wellbore temperature distribution under different injection pressures.

3.3.2. Effect of Injection Temperature on Wellbore Temperature

The wellbore temperature at different injection temperatures was calculated as shown in Figure 5. As the injection temperature rose from 60 °C to 200 °C, the temperature of the wellbore increased significantly. However, the higher the injection temperature was, the faster the cooling rate was. The temperature of the wellbore did not change significantly when the depth of the well was 500 m down. It can be seen that the injection temperature has a great influence on the upper end of the wellbore and can significantly increase the wellbore temperature at the depth prone to plugging.

3.3.3. Effect of Injection Volume on Wellbore Temperature

The wellbore temperature at different injection rates was calculated, and the results are shown in Figure 6. As the injection volume increased from 600 m^3/h to 1200 m^3/h, the temperature of the whole section of the wellbore increased significantly. However, when the injection volume was lower, the cooling rate of the wellbore was faster, and the lowest temperature point was in a shallow position, so the heating effect of the whole section was poor. It can be seen that the injection volume has a great influence on the whole wellbore.

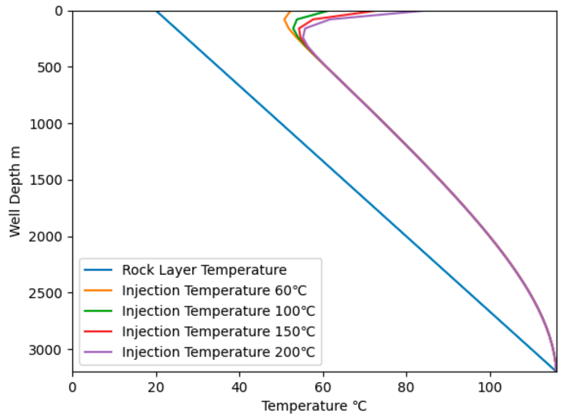


Figure 5. Wellbore temperature distribution under different injection temperatures.

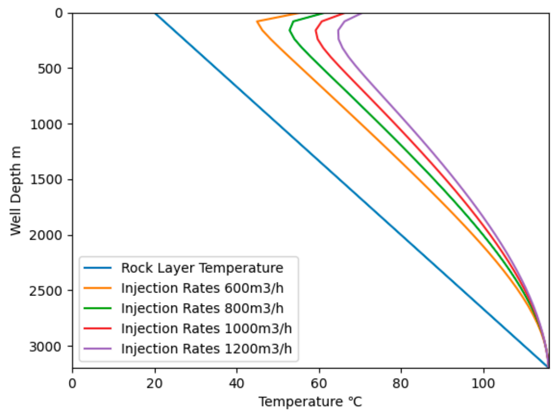


Figure 6. Wellbore temperature distribution under different injection rates.

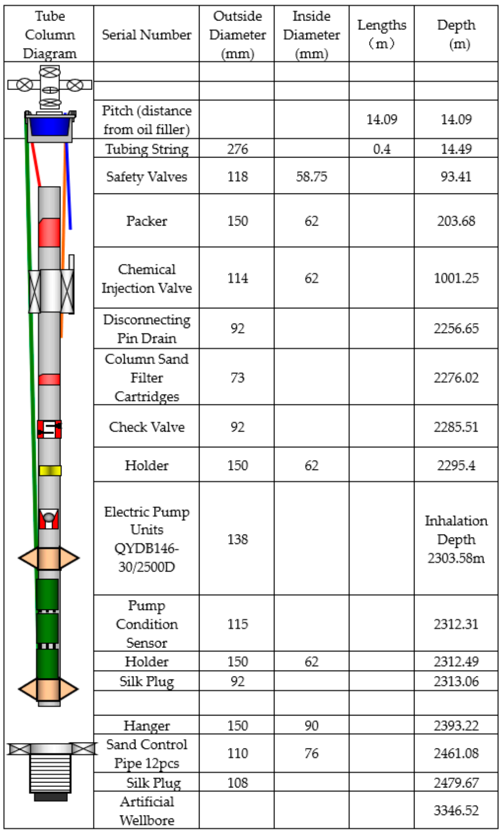
4. Wax Removal and Plug Removal Design

The A1 well in Bohai Sea of China was drilled and the tree was installed in 2019, and the production string of this well is shown in Figure 7. Hot nitrogen is injected mainly through the production head, cables, packers, centralizers, tubing, electric pump, single flow valves, sand filter screens, oil drain valves, and safety valves. Among these tools, the current packer, which was installed 200 m away from the wellhead, has a temperature limit (80 °C) and is susceptible to high-temperature fluids, with it requiring special attention in program design.

4.1. Wellhead Injection Temperature Optimization

The purpose of this optimization is to ensure that after hot nitrogen injection, the entire wellbore can be heated to a temperature higher than the wax extraction point and that the temperature at the packer does not exceed the maximum packer temperature of 80 °C.

According to the rated displacement of the nitrogen production equipment, the injection rate of nitrogen is 1200 m^3/h. The casing temperature distribution and tubing temperature distribution under different injection temperatures were calculated; the results are shown in Figures 8 and 9.



Tube Column Diagram	Serial Number	Outside Diameter (mm)	Inside Diameter (mm)	Lengths (m)	Depth (m)
	Pitch (distance from oil filler)			14.09	14.09
	Tubing String	276		0.4	14.49
	Safety Valves	118	58.75		93.41
	Packer	150	62		203.68
	Chemical Injection Valve	114	62		1001.25
	Disconnecting Pin Drain	92			2256.65
	Column Sand Filter Cartridges	73			2276.02
	Check Valve	92			2285.51
	Holder	150	62		2295.4
	Electric Pump Units QYDB146-30/2500D	138			Inhalation Depth 2303.58m
	Pump Condition Sensor	115			2312.31
	Holder	150	62		2312.49
	Silk Plug	92			2313.06
	Hanger	150	90		2393.22
	Sand Control Pipe 12pcs	110	76		2461.08
	Silk Plug	108			2479.67
	Artificial Wellbore				3346.52

Figure 7. Production string diagram.

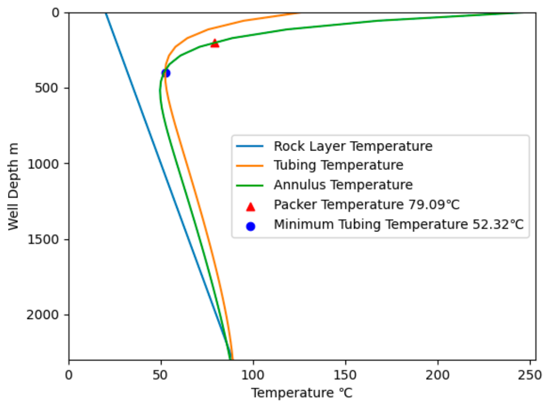


Figure 8. Temperature profile at the injection temperature of 250 °C.

As can be seen from the figure, when the injection temperature is 250 °C, the packer temperature is 78.62 °C, which is just within the safe operating range of the packer, and the temperature in the tubing is greater than the wax precipitation temperature. When the injection temperature is 60 °C, the lowest temperature of the tubing is 46.89 °C, and the temperature inside the tubing is just higher than the wax precipitation temperature. Therefore, the temperature range of 60–250 °C can be selected during the construction process.

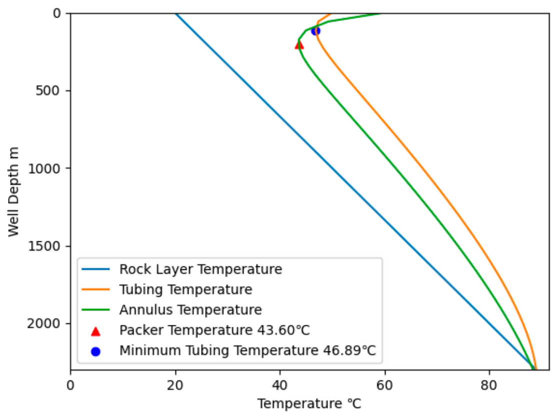


Figure 9. Temperature profile at the injection temperature of 60 °C.

4.2. Equipment Matching Proposal

(1) Nitrogen production equipment

Membrane separation nitrogen was made by using a polymer hollow fiber membrane to separate nitrogen from oxygen and other gases in the air with different permeabilities. At present, the company has skid-mounted membrane nitrogen production equipment, as shown in Table 1 and Figure 10.

Table 1. Nitrogen production equipment properties.

Name	Nitrogen Production Equipment
Nitrogen purity	95–99%
Air inlet pressure	≥2.4 MPa
Nitrogen outlet pressure	≥2.15–2.2 MPa
Power supply	380 V, 50 Hz/440 V, 60 Hz
Protection class	P55

Figure 10. Nitrogen production equipment.

(2) Air compressor equipment

At present, the company has skid-mounted membrane air compressor equipment, as shown in Table 2 and Figure 11.

4.3. Construction Process

(1) Open the main valve and wax removal valve of the tree and prepare to pump 60–250 °C nitrogen for circulating washing;
(2) Start the pump slowly, keep the pump pressure at 10 MPa, and observe the return situation;

(3) After determining the normal return, keep the hot nitrogen pumped continuously, keep the pump pressure at 15 MPa, and carry out hot washing;
(4) For hot nitrogen plugging, observe the return situation when the pump enters; when the plugging effect does not reach the effect, increase the pump pressure and squeeze hot nitrogen at the pump pressure of 20 MPa;
(5) During hot nitrogen plugging, observe the change in return and wellhead pressure at any time;
(6) After the wellbore is established, convert it to large displacement hot washing.

Table 2. Air compressor equipment properties.

Name	Air Compressor Equipment
Type	SULLAIR 1350/350
Displacement	35.4 m^3/min
Exhaust pressure	2.4 MPa
Exhaust temperature	$\leq$120 °C
Oil content of exhaust gas	5–8 ppm
Full load/no load speed	1800/1200-rpm

Figure 11. Air compressor equipment.

5. Conclusions

In this paper, a precipitation test for waxy crude oil was carried out by using the water bath observation method from a real crude oil sample in a block from the Bohai Sea of China. The wax precipitation point temperature of the experimental crude oil sample was about 45 °C. Based on the principle of thermodynamics, the heat transfer model of temperature variation with well depth under the condition of hot nitrogen circulation is proposed, and the law of heat loss of hot nitrogen and the change in tubing temperature and casing temperature with well depth was analyzed. Based on the actual working conditions and production string structure of well A1 in the Bohai Sea of China, the optimization method of hot nitrogen injection temperature was proposed. Under the rated injection volume of 1200 m^3/h of the ground equipment, in order to achieve the function of clearing wax and unblocking, and to make the packer work safely, the injection temperature range is 60–250 °C. According to the existing equipment of the company, the process flow of hot nitrogen circulation wax removal and plug removal was proposed.

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